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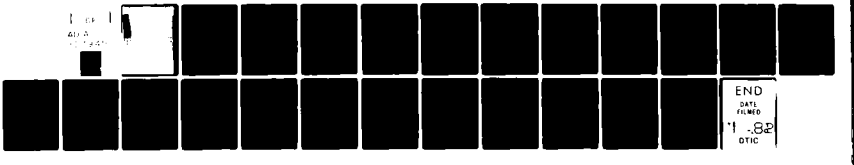

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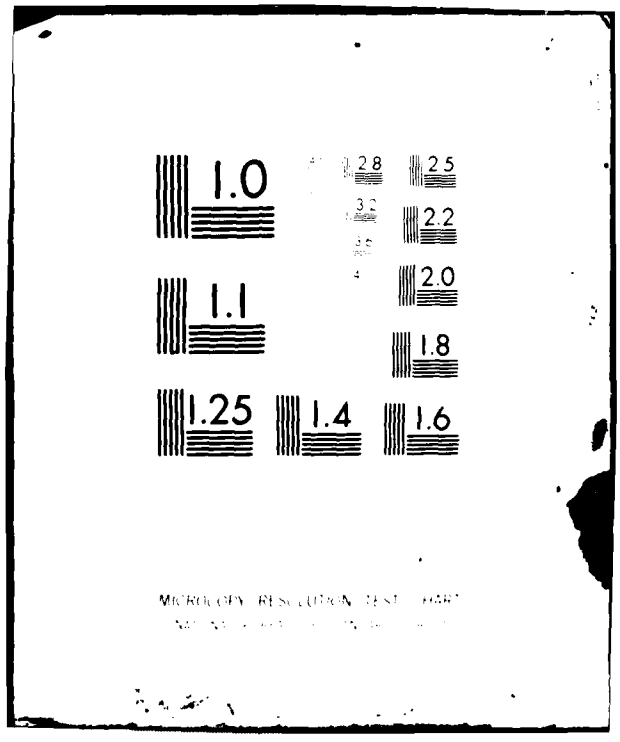
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COMPARISON OF STATE TABLES AND ORDNANCE PUBLICATIONS FOR TROUBLESHOOTING DIGITAL EQUIPMENT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Eight Navy technicians participated in an evaluation of the effectiveness of state tables in troubleshooting the Missile Control Unit (MCU) of the NATO Seasparrow Surface Missile System. In a repeated-measures design, the technicians used either state tables or ordnance publications (OPs) to troubleshoot 96 problems in the MCU. With state tables, 31 of 48 problems were solved in 1499 minutes. With OPs, nine of 48 problems were solved in 2027 minutes. Twice as many checks were made with OPs as were made with

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state tables. Seven of the eight subjects rated state tables as excellent or good. With OPs, the ratings were lower and less consistent, ranging from poor to good. In general, state tables were preferred over OPs. Results are discussed in terms of state table implementation in the fleet.

FOREWORD

This research and development was conducted in response to Navy Decision Coordinating Paper, NDCP-Z0828-PN, Performance Aids Test and Evaluation, under the sponsorship of the Deputy Chief of Naval Operations (OP-01). This work seeks to further the objectives of the NDCP, which are: to define the state-of-the-art in Job Performance Aid (JPA) technology; to develop a conceptual model for an integrated JPA-based personnel system, including cost benefits and trade-off analysis; to test the JPA concept; and to quantify performance increments and cost benefits obtainable from various applications.

This report compares the effectiveness of the state tables and ordnance publications as troubleshooting aids.

Sincere appreciation is expressed to the personnel of the Combat Systems Technical Schools Command at Mare Island, California, for their assistance in conducting this study. GMMC K. Randall deserves a special note of appreciation for sharing his expertise and spending many 12-hour days monitoring the evaluation. Appreciation is extended to CW04 J. Davis and FTCM J. Fuller who contributed their time during the planning phase of this study.

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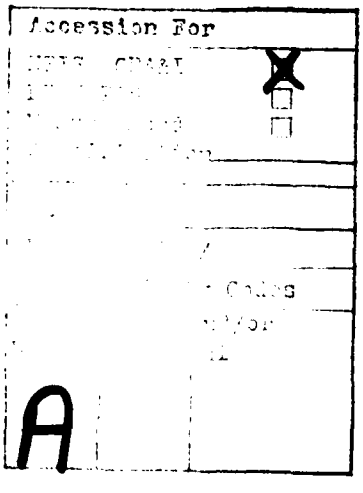

SUMMARY

Problem

Binary digital circuit elements alternate between two states, which are often referred to as "1" and "0" or as "high" and "low." When troubleshooting digital equipment, it is not enough to know whether the output of a circuit element is high or low--it is necessary to know whether the output is high or low at specific points in time. Numerous job performance aids (JPAs) have been developed to assist technicians in troubleshooting electronic equipment, but none of those in current use address the problem of timing in digital systems. A recently developed JPA, the state table, provides technicians with time-related troubleshooting information, but the concept had not been evaluated by the Navy.

Objective

The objective of this research was to compare state tables with an existing form of troubleshooting documentation, the ordnance publication (OP).

Approach

Eight Navy technicians, after receiving instructions in the use of state tables, were directed to troubleshoot 12 problems on the Missile Control Unit (MCU) of the NATO Seasparrow Surface Missile System (NSSMS). Each subject used state tables for six problems and OPs for six others. Problems of three levels of difficulty were used: easy, medium, and hard. The subjects were given a maximum time limit on each problem: 30 minutes for easy problems, 45 for medium, and 60 for hard. The performance of each subject was evaluated and compared on the basis of success rate, time required, the number of checks required, and the number of valid checks performed. (A check was considered valid if it was (1) prescribed by the troubleshooting document and (2) correctly interpreted by the subject.) By questionnaire, the subjects were then asked to rate and compare state tables and OPs.

Findings

Using state tables, the subjects solved 31 problems in 25 hours. With OPs they solved only nine problems, and took 33.8 hours to do so. A nonparametric test, the Wilcoxon Matched-Pairs Signed-Ranks Test, indicated that both the increase in the number of problems solved and the decrease in troubleshooting time were associated with a single factor--use of state tables.

With state tables, 710 checks were made, with 606 of them valid. With OPs, 1404 checks were made, with 1062 valid.

Seven of the eight subjects rated the state tables as excellent or good for all problem types. OPs were rated as good or adequate by seven subjects for easy problems, by six for medium problems, and by only three for hard problems. All eight subjects preferred state tables over OPs for medium and difficult problems.

Conclusions

The results of this research indicate that state tables are effective JPAs for troubleshooting digital equipment in the NSSMS. The state tables, supported by a troubleshooting guide, enabled technicians to isolate over three times the number of faults in 25 percent less time.

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Recommendations

1. The Navy should incorporate the state tables and troubleshooting guide into NSSMS documentation.

2. The Navy should provide potential users of state tables with adequate training, including hands-on experience.

3. The state table technique should also be compared with the troubleshooting techniques contained in conventional technical manuals, in functionally-oriented maintenance manuals, and in other documents that have been prepared to facilitate the troubleshooting of digital electronic equipment.

4. Extension of this comparison to include fleet personnel would provide a better understanding of the positive and negative aspects of using state tables for troubleshooting.

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INTRODUCTION

Problem

Binary digital circuit elements alternate between two states, which are often referred to as "1" and "0" or as "high" and "low." When troubleshooting digital equipment, it is not enough to know whether the output of a circuit element is high or low--it is necessary to know whether the output is high or low at specific points in time. Numerous job performance aids (JPAs) have been developed to assist technicians in troubleshooting electronic equipment, but none of those in current use address the unique problem of timing in digital systems. A recently developed JPA, the state table, provides technicians with time-related troubleshooting information but the concept had not been evaluated by the Navy.

Purpose

The objective of this research was to compare state tables with an existing form of troubleshooting documentation, the ordnance publication (OP).

Background

Maintenance of a system requires both planned and unplanned maintenance. Planned maintenance (e.g., cleaning, inspecting, adjusting, replacing, etc.) is performed on a periodic basis to ensure continued operation of the system. These tasks are generally well defined, with specific start and end points, and the time required to perform each task is fairly predictable. Unplanned maintenance actions (i.e., those needed to repair a malfunctioning system) include troubleshooting and removal and replacement actions.

Troubleshooting is a deductive process that requires the technician to make a series of logical decisions based upon observation or measurement of the states of various circuit elements. Conventional technical manuals, functionally-oriented maintenance manuals (FOMMs), and other JPAs have been designed to assist technicians in making these decisions quickly and correctly, but troubleshooting remains the most difficult maintenance task. This is especially true in digital equipment and systems.

Problems in Digital Systems Maintenance

In analog circuits, each signal follows a single path, though it may occasionally loop or branch out. The technician can usually trace the signal from its origin to its output and isolate a problem to a faulty circuit element by a process of elimination.

It is seldom possible to use such techniques when troubleshooting digital systems. In a digital circuit, a given circuit element may serve different purposes at different times, and digital data may flow through different paths from one instant to the next. Because of the complex branching in digital systems, a fault may have wide-ranging effects that do not appear, initially, to have any connection with each other or with the faulty circuit element.

Digital circuit elements switch back and forth between two states and being in the wrong state, or between states, constitutes an error. The proper state of each element is a function of time. An error may or may not be detected at all, depending upon the mode the system is in and the timing of events (i.e., an error may be undetectable if the state of the malfunctioning component does not matter during the time the system is being observed, a distinct possibility with digital systems).

For example, assume that the output of a certain flip-flop is supposed to be high only when data are entering the system (flip-flops are common digital circuit elements). A failure that caused this flip-flop's output to be high at all times would be detected only if a test was made when data were not entering the system.

Built-in Test Equipment (BITE) and Diagnostic Programs

To compensate for their complexity, digital systems are often designed with built-in test equipment (BITE) and diagnostic programs that perform, automatically, many of the complex tests required to isolate digital equipment malfunctions. BITE and diagnostics are expensive and their comprehensiveness is limited by their cost. For example, if a diagnostic has been developed to isolate 90 percent of all faults, the cost of increasing fault isolation by 1 or 2 percent could double the cost of the diagnostic (Porta, 1979). Regardless of cost, however, even the most comprehensive diagnostics cannot isolate all faults in a system and some percentage of the troubleshooting must be done by more or less well-trained and experienced technicians.

Currently Available Job Performance Aids (JPAs)

In addition to BITE and diagnostics, various JPA formats have been developed to help the technician troubleshoot digital equipment. One approach complements the diagnostics by furnishing functional block diagrams that lead the troubleshooter to a suspected group of components where the fault may be located. This approach also indicates additional fault groups that the technician can test if the fault is not found in the initially identified group.

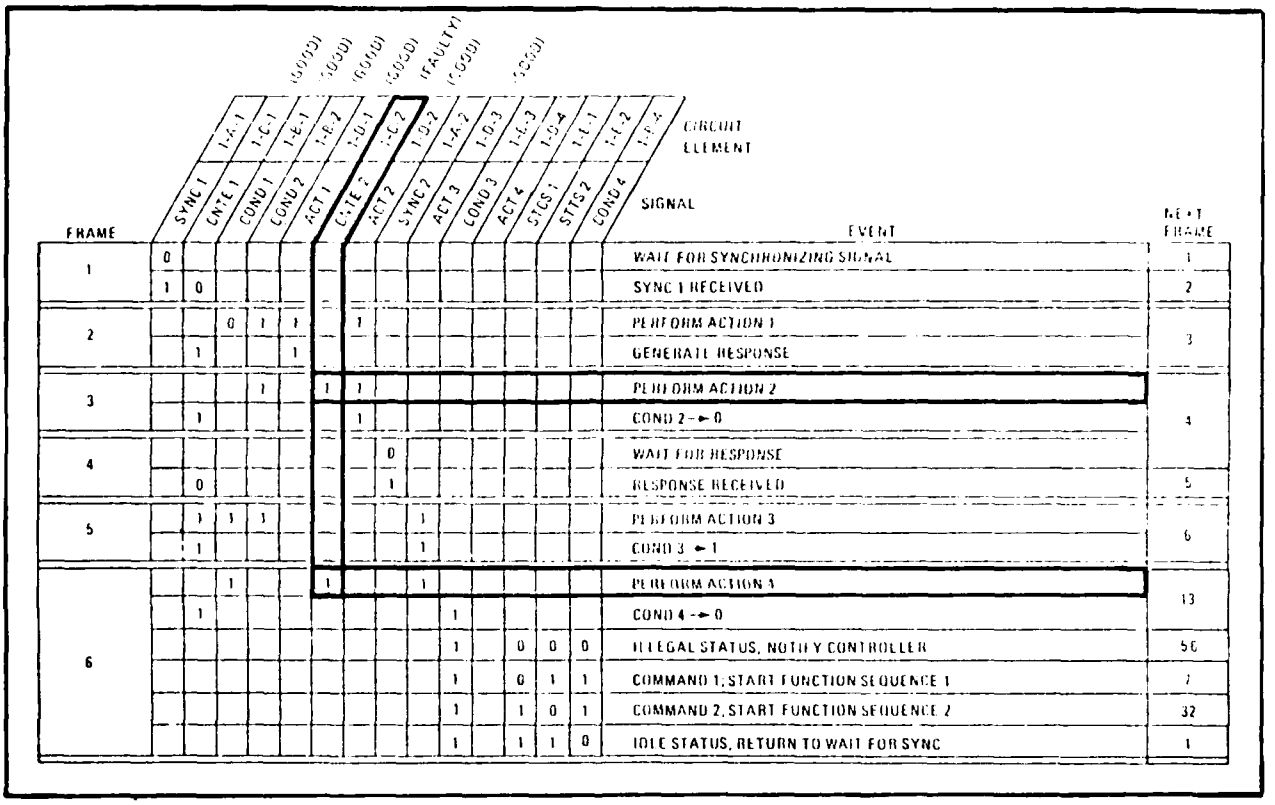
Functionally oriented maintenance manuals (FOMMs) have been adapted to digital systems by the addition of timing diagrams, but the timing information has not been integrated with logic-flow information. The technician is therefore required to mentally integrate the two types of information while troubleshooting.

The increasing use of digital components has made the troubleshooting approach of current JPAs generally inadequate. When JPAs were developed for analog equipment, all fault symptoms were identified and corrective procedures were developed for each symptom or set of symptoms. But since digital components serve multiple functions, and since digital signal paths are seldom straightline functions, an almost infinite number of symptoms are possible in a large digital system. The technician who troubleshoots digital systems needs a complete functional understanding of the system, usually attained after many years of training and experience. A recently developed JPA, the state table, may make it possible for less experienced technicians to troubleshoot digital systems.

DESCRIPTION OF THE STATE TABLE CONCEPT

State tables provide concise, uncomplicated, and time-related representations of the functions of digital equipment and systems. They not only describe the sequence of events required to execute each function, they also show the logic signal combinations that characterize each event. State tables are system-oriented, thus enabling technicians to approach troubleshooting tasks from the standpoint of system characteristics rather than equipment characteristics. Within each state table, normal system characteristics are correlated with the logic states of selected circuit elements in a way that indicates where one should look for the fault.

Figure 1 illustrates the state table format. The circuit elements are listed across the top and the states of the elements are represented by zeros (low state) and ones (high state). The events enabled by specific states of the circuit elements are listed on the right side. For example, the event SYNC 1 RECEIVED is enabled when 1-A-1 is high (1) and 1-C-1 is low (0).



FRAME	SYNC 1 (1-A-1)	CNTL 1 (1-C-1)	COND 1 (1-E-1)	COND 2 (1-E-2)	ACT 1 (1-D-1)	CNTL 2 (1-C-2)	ACT 2 (1-D-2)	SYNC 2 (1-A-2)	ACT 3 (1-D-3)	COND 3 (1-E-3)	ACT 4 (1-D-4)	STS 1 (1-E-1)	STS 2 (1-E-2)	COND 4 (1-E-4)	SIGNAL EVENT	NEXT FRAME
1	0														WAIT FOR SYNCHRONIZING SIGNAL	1
	1	0													SYNC 1 RECEIVED	2
2			0	1	1		1								PERFORM ACTION 1	3
		1			1										GENERATE RESPONSE	
3				1		1	1								PERFORM ACTION 2	4
		1					1								COND 2 ← 0	
4								0							WAIT FOR RESPONSE	
		0						1							RESPONSE RECEIVED	5
5		1	1	1					1						PERFORM ACTION 3	6
		1							1						COND 3 ← 1	
6			1			1			1						PERFORM ACTION 4	13
		1								1					COND 4 ← 0	
										1		0	0	0	ILLEGAL STATUS, NOTIFY CONTROLLER	56
										1		0	1	1	COMMAND 1, START FUNCTION SEQUENCE 1	7
										1		1	0	1	COMMAND 2, START FUNCTION SEQUENCE 2	32
										1		1	1	0	IDLE STATUS, RETURN TO WAIT FOR SYNC	1

Figure 1. State Table (typical).

To use a state table successfully, the technician must understand the various functions of the equipment and be able to recognize malfunctions. As an aid, troubleshooting guides have been developed to correlate BITE indications with the state tables. Typically, the troubleshooting guide and state tables are used together as follows:

1. The technician initiates a built-in test and observes which fault indicators are illuminated.

2. The technician uses the troubleshooting guide to determine the area where the fault is most likely to be.

3. The guide directs the technician to the state table that covers the area indicated in step 2.

4. The technician notes which functions are good and which are not, and uses the state table to isolate the fault to a single circuit element.

5. The technician compares the actual states of the suspect circuit elements with the states prescribed for them in the state table to verify their condition.

Figure 2 presents an example of how a state table can be used to isolate a defective circuit element. In this example, a preliminary investigation indicated that functions 2, 3, and 6 were good and that 1, 4, and 5 were faulty. The state table shows that only one circuit component, C-5, is related to all three faulty functions.

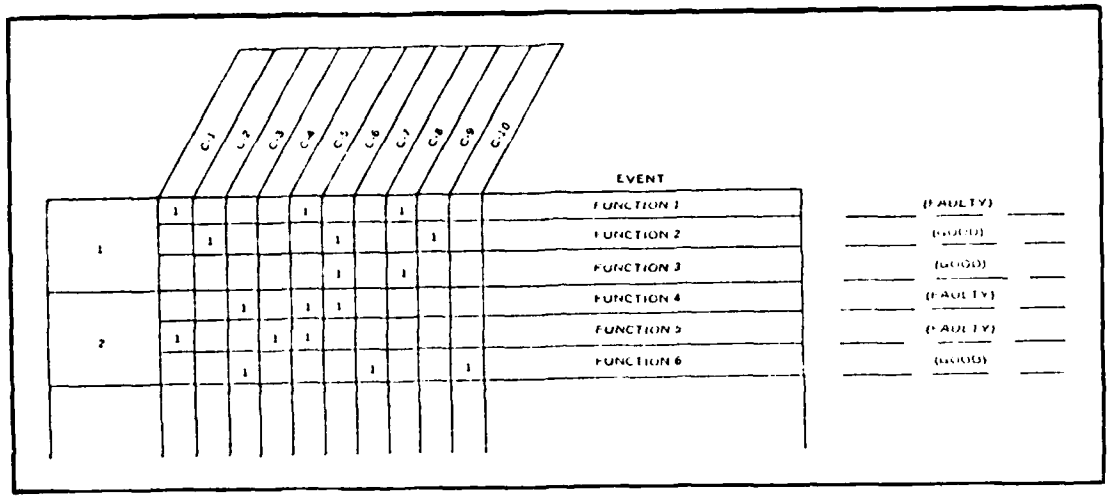


Figure 2. State table example.

During the analysis that precedes state table development, the system is described function by function and the state tables are developed accordingly. The malfunction indications of the system are then considered and integrated into the troubleshooting guide.

Thurmond and Booher (1979), in comparing the adequacy and cost of preparation of state tables with other documentation, found that state tables offered the following advantages:

1. Complete digital systems content coverage.
2. Ease of use.
3. Improved display of information.
4. Improved troubleshooting training.
5. Reduced skill and knowledge requirements.

APPROACH

Subjects

This evaluation should be considered a pilot test because only eight subjects were tested during the 2-week evaluation period. The relatively small N was due to the difficulty of obtaining subjects with the necessary training and experience on the Missile Control Unit (MCU) of the MK-29 NATO Seasparrow Surface Missile System (NSSMS).

Four of the subjects were students who had just graduated from the MK 29 NATO Launcher School at the Combat Systems Technical Schools Command (CSTSC), Mare Island, California. Three of the students had attended Basic Electricity and Electronics School, Gunners Mate "A" School, and the MK 29 NATO Launcher School. The fourth student had attended seven schools before attending the MK 29 NATO Launcher School. The students had been in the Navy from 2 to 3 years.

The fifth and sixth subjects were MK 29 NATO Launcher instructors; the seventh was a NATO Fire Control System instructor; and the eighth was a Fire Control Technician awaiting assignment to a school. The instructors had been in the Navy from 8 to 14 years and the Fire Control Technician had been in for 6 years. The last two mentioned subjects had not received any training on the MCU of the NSSMS.

Equipment

The MCU of the NSSMS was selected for use in this evaluation because it has a high failure rate and the existing documentation did not appear to be adequate for technical support. The state tables and troubleshooting guide for the MCU were developed by Hughes Aircraft Company, Fullerton.

Procedure

Each subject was given 3½ days of instruction in state table usage, followed by 6 days of performance testing. A partial repeated measures design was used in which each subject attempted to solve 12 problems in four separate sessions. Each subject was tested individually, and each session lasted approximately 2¼ hours.

During the testing, subjects were divided into two groups, each consisting of two MK 29 students, one MK 29 instructor, and either the Fire Control System Instructor or the Fire Control Technician. The order in which each group used the troubleshooting methods was varied: One group used state tables to solve problems during their first and last sessions, and OPs during their second and third sessions; the other group used OPs in their first and last sessions, and state tables in their second and third sessions. Testing sessions were held in alternating sequence, a session with one group being followed by a session with the other.

Each session consisted of three problems: one easy, one medium, and one hard. The problems were casualties drawn from a master casualty file developed for MCU troubleshooting training by CSTSC. The casualty file was developed before state tables were introduced to CSTSC. The levels of problem difficulty were defined as:

1. Easy (E)--a casualty with an instruction cycle of 2-3 instructions or 3-4 control signals.

2. Medium (M)--a casualty with an instruction cycle of 4-6 instructions or 6-10 control signals.

3. Hard (H)--a closed loop casualty that could have an unlimited number of instruction cycles or control signals. These were CROM addressing faults and DUS 8 instruction cycle faults. (CROM and DUS 8 are computer component designations.)

Easy problems had a 30 minute time limit; medium, 45 minutes; and hard problems, 60 minutes. There were four similar problems for each level of difficulty, and the order of presenting the problems was varied (counter balanced) to eliminate order effects. The independent variable of interest was the type of troubleshooting document (OP or state table) used by the subject. The experimental design is given in Table 1.

Table 1

Experimental Design

Type of Troubleshooting Problem	Number of Observations (Problems Attempted)	
	State Tables	Ordnance Publications
Easy	16	16
Medium	16	16
Hard	16	16

Note. The number of observations was obtained by having each of the eight subjects solve two problems in each cell.

Data

The following dependent measures were determined:

1. Number of problems (E, M, or H) solved within the time limits.
2. Amount of troubleshooting time.
3. Total number of checks (both valid and invalid).
4. Number of checks that were valid.

Valid checks were those checks that were (1) prescribed by the troubleshooting document and (2) interpreted correctly by the technician. Invalid checks were those that were not prescribed by the documented procedures, or prescribed checks that were misinterpreted.

Qualitative data were collected by a questionnaire that required subjects to rate state tables and OPs for each level of difficulty, and to compare state tables with OPs. (The questionnaire is shown in Figure 3.)

Subject ID _____ Session _____

A. What is your reaction to (state tables/OPs) for problem:

	Excellent	Good	Adequate	Less than Adequate	Poor
1	( )	( )	( )	( )	( )
2	( )	( )	( )	( )	( )
3	( )	( )	( )	( )	( )

B. Were the (state tables/OPs) easy to follow for problem:

	Yes	No
1	( )	( )
2	( )	( )
3	( )	( )

C. Were the (state tables/OPs) helpful in locating faults for problem:

	Yes	No
1	( )	( )
2	( )	( )
3	( )	( )

D. Which technique did you prefer for each problem?

	State Tables	OPs	Both
1	( )	( )	( )
2	( )	( )	( )
3	( )	( )	( )

Figure 3. Questionnaire

E. Were the state tables an improvement over OPs on your ability to detect and troubleshoot for each problem?

	Yes	No
1	( )	( )
2	( )	( )
3	( )	( )

F. Did the state tables provide a more logical sequence to follow for problem solving than the OPs?

	Yes	No
1	( )	( )
2	( )	( )
3	( )	( )

G. Which were more helpful in solving problems?

	State Tables	OPs	Neither
1	( )	( )	( )
2	( )	( )	( )
3	( )	( )	( )

Figure 3. (Continued)

RESULTS

Since none of the subjects had used state tables in an operational setting, the first problem (the easy one) of the first session served as a practice problem and the subjects were given constructive feedback on their procedures. The problem was repeated during the second session with state tables. The data from the repeated problem were included in the results to keep the cell sizes equal. (The MCU is complex enough that there is little change in the likelihood of solving a problem repeated only once.) All subjects had used OPs in operational settings, so no OP practice problems were included.

With state tables, the eight subjects solved 31 of 48 problems in 25 hours. With OPs, they solved 9 of 48 problems in 33.8 hours. The means and standard deviations are given in Table 2.

Table 2

Problems Completed and Troubleshooting Time

	Problems Completed per Subject		Troubleshooting Time[a] (Minutes)	
	OP	State Tables	OP	State Table
Mean	1.125	3.875	253.375	187.375
Standard Deviation	1.246	1.458	24.951	36.265

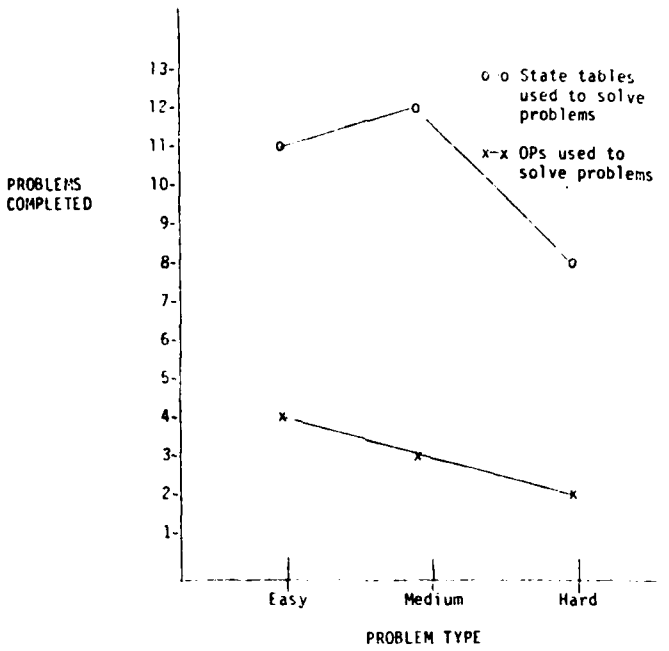
[a]Time per subject spent on all 12 problems attempted.

A nonparametric test, the Wilcoxon Matched-Pairs Signed-Ranks Test (Roscoe, 1975), was used to test the null hypothesis that state tables and OPs lead to no difference in troubleshooting time or number of completed problems. The hypothesis was rejected, with all differences in the same direction ($\alpha = .01$). Thus, both the increase in the number of problems completed correctly and the decrease in the troubleshooting time are attributable to a single factor--the use of state tables.

When the evaluation results were correlated to problem type, it was discovered that the level of difficulty had different effects on the time required to solve problems with state tables and OPs, as well as varying effects on the average number of problems solved by each subject. These differences are summarized in Figures 4 and 5.

Additional measures included total checks and the number of those checks that were valid. With state tables, 710 checks were made, of which 606 (85%) were valid. With OPs, 1444 checks were made, of which 1062 (74%) were valid.

The questionnaire provided qualitative data. Table 3 presents the ratings given by the eight subjects for each problem type and documentation type. Table 4 summarizes their documentation preferences for each level of problem difficulty.



Note. Each subject attempted to solve two problems with each type of documentation at each level of difficulty.

Figure 4. Number of problems solved (by problem type) by eight subjects.

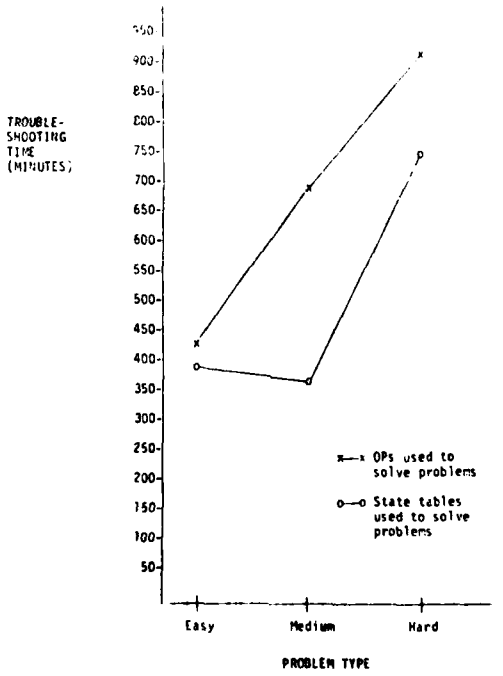


Figure 5. Troubleshooting time taken by subjects when solving easy, medium, and hard problems.

Table 3

Subject Ratings of State Tables and OPs for Easy, Medium, and Hard Problems

Problem Type	Number of Subjects Rating Documentation as: Excellent	Good	Adequate	Less than Adequate	Poor
State Tables					
Easy	5	2	0	1	0
Medium	5	2	1	0	0
Hard	6	1	0	1	0
OPs					
Easy	0	3	4	1	0
Medium	0	4	2	0	2
Hard	0	1	2	1	4

Note. N = 8 for all cells.

Table 4

Preference Rating by Problem Type

Problem Type	Number of Subjects who Preferred: State Tables	OPs	No Preference
Easy	6	0	2
Medium	8	0	0
Hard	8	0	0

Note. N = 8 for all cells.

DISCUSSION AND CONCLUSIONS

Although this evaluation was a pilot test with the noted constraints, the evidence supports the conclusion that state tables are effective troubleshooting JPAs for digital systems. When compared with existing documentation for the NSSMS, the state tables enabled users to isolate more faults. The mean number of problems completed correctly by each subject was 3.875 when state tables were used; it was only 1.125 when OPs were used. In addition, with state tables the troubleshooting time for the 12 problems was reduced by more than 25 percent (2027 minutes overall for OPs versus 1499 minutes for state tables).

With state tables there was more variability in the subject's troubleshooting times. The standard deviation for state tables was 36.265, while for OPs it was only 24.951. There are two reasons for this variability. First, when OPs were used, troubleshooting times approached the time limits for all problem types, thus reducing the overall range of times. With state tables, however, some subjects solved the easy and medium problems in extremely short periods of time, while spending a relatively long time on hard problems. For example, the medium difficulty problem in the second session with OPs required the full time limit, 45 minutes, for all subjects; with state tables the mean was only 8.25 minutes. At the same time, the mean for the hard problem in the second session with OPs was 58.125 minutes, while with state tables, the mean was 49.50. The time with OPs varied only about 13 minutes, but with state tables it varied over 40 minutes.

The second reason for the variability in troubleshooting times with state tables was the newness of the technique and the experience level of the subjects. Experienced technicians (i.e., the instructors) had to "relearn" troubleshooting with the state table technique, which could have produced interference on some problems. Also, the inexperienced technicians (i.e., the recent graduates) may have found it easier to apply the state table technique in some areas and not in others.

When problem difficulty is correlated with the type of documentation, the results do not appear to be consistent for state tables. However, the classification of problems as easy, medium, and hard was based on previous experience with OPs, not state tables. When examining the data for OPs, the number of problems solved and the troubleshooting time are consistent with the problem types. For state tables, however, the medium problem type does not appear to be appropriately classified. It may be an anomaly associated with one particular problem; that is, state table logic may be exceptionally superior to OP logic for solving that problem.

Almost twice as many checks were required when using OPs as were required when using state tables. The large difference in total checks is reflected in the number of valid checks: There were 400 more valid checks with OPs than with state tables. It appears that state tables provide an efficient means of fault isolation. With fewer checks, and with more of them being valid, a troubleshooter can reduce equipment down time significantly.

The relative superiority of state tables over OPs is enhanced when the users' subjective ratings and comparisons are included. Seven of the eight subjects rated the state tables as excellent or good for all problem types. OPs, on the other hand, were rated as good or adequate by seven subjects for easy problems, by six for medium problems, and by only three for hard problems. Finally, all eight subjects preferred state tables over OPs for medium and difficult problems, and six preferred them to OPs for easy problems.

RECOMMENDATIONS

Based on the results of this pilot test, it is recommended that the Navy incorporate the state tables and troubleshooting guide as part of the present NSSMS documentation. If this recommendation is accepted, the state tables and troubleshooting guide will need to be given some type of introduction (i.e., the potential users should have hands-on training with state tables.) Failure to provide an introductory framework for the state table technique could lead to misinterpretation and rejection by the fleet.

Extension of this comparison to include other equipment and more personnel would provide additional information on the positive and negative aspects of using state tables for troubleshooting.

A more comprehensive evaluation should be conducted. The state table technique should be compared to conventional technical manuals, FOMMs, and other JPAs that have been prepared to facilitate troubleshooting digital electronic equipment.

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